

UNITED STATES AIR FORCE RESEARCH LABORATORY

CONTENT VALIDITY REQUIREMENTS FOR SIMULATED SENSOR IMAGERY

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FOR THE COMMANDER



MARIS M. VIKMANIS
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PREFACE

This survey of "Content Validity Requirements for Simulated Sensor Imagery" was conducted by a team from PAMAM – Human Factors Engineering (1989) Ltd., Hod Hasharon Israel. Dr. Michael Brickner and Ms. Ayelet Oettinger were the researchers who conducted the project.

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SUMMARY

Real sensor imagery is obtained with actual sensors, installed on their platforms and imaging actual environments. Sensor imagery simulation is used to create surrogate sensor imagery generated under simulated environments and conditions. Imagery simulation capabilities have been created to support procedural training, weapon-system-training requirements, mission rehearsal, system research and development and human-factors studies. The present study was designed to investigate sensor imagery simulation capabilities and requirements, with specific emphasis on SAR (synthetic aperture radar) and FLIR (forward looking infrared) imagery and to develop a framework for analyzing required simulation fidelity for various applications.

Physics-based imagery simulation tools are the most recently developed and the most advanced in terms of their capabilities. These tools model the major parameters that impact real sensor images: the environment (terrain and atmosphere), the radiometric equations, and the sensor system. A survey was conducted to identify existing sensor imagery simulation products and applications. The study also includes a literature review on object recognition and sensor image quality attributes that affect object recognition and acquisition performance.

The concept "simulation fidelity" is used to describe the effective differences between a real and a simulated system. Ideally the simulated image should be identical to its real world counterpart (i.e., perfect simulation fidelity). However, perfect simulations may not be feasible (technically or financially) and may not always be necessary. The central issue of the present study is to identify fidelity requirements for various uses of simulated sensor imagery. In theory, state-of-the-art, physics-based simulation programs, are capable of producing very high-fidelity simulations of sensor imagery. In practice, however, simulation fidelity depends on the completeness and accuracy of all components of the simulation, i.e., the representation of terrain, terrain-objects and human-placed objects, atmospheric conditions, the radiometric equations and the representation of the specific sensor system. The efforts required to produce high-fidelity simulations may prove to be impractical for many applications. Therefore, the necessary fidelity of the simulation should be determined by the requirements of the application. These requirements were identified for various applications, first on the basis of the theoretical analysis and then through structured interviews with Subject Matter Experts (SMEs).

The main obstacles for creating high fidelity FLIR and SAR simulation with physics-based simulation tools, for both SAR and FLIR, are related to the very limited availability of material-maps and to the difficulty in representing human-made ground objects. In addition, interactions between components within and between objects (particularly in FLIR) are hard to represent.

The sensor-imagery simulation-fidelity model, presented herein, proved effective, it was easy for the SME to relate to the concepts and come up with the required evaluations. SME provided significant data on the required simulation fidelity of various image components in simulated SAR and FLIR images, for different tasks (photo interpretation, reconnaissance, target recognition & designation) and for different simulation applications (training, mission rehearsal).

SECTION I

INTRODUCTION

Background

Real sensor imagery can be obtained with actual sensors, installed on their platforms and imaging real environments. Simulated sensor imagery is used to create sensor imagery generated under simulated conditions and environments. Imagery simulation capabilities have, in general, been created to support procedural training, weapon-system-training requirements, operator pre-briefing and mission rehearsal, system research and development and human-factors studies.

No research has been conducted to establish the content fidelity requirements of simulated imagery in the various contexts, and particularly, in the context of object recognition and target acquisition performance.

Objectives

The present study was designed to perform a survey of sensor imagery simulation capabilities and requirements, with emphasis on SAR (synthetic aperture radar) and FLIR (forward looking infrared) imagery. The study includes a literature search and review of sensor image quality attributes and of their effects on object recognition and target acquisition performance. Applications for simulated imagery have been identified and their features are described in the report. Qualitative/quantitative requirements for these applications have been derived in terms of image quality and image content. A set of criteria for the performance of pattern and object recognition and target acquisition tasks, with each type of simulated imagery (FLIR and SAR), has been developed. The proposed set of criteria for the evaluation of required simulation fidelity of various types and purposes was examined with the help of ten expert users of sensor imagery (subject matter experts - SMEs).

Sensor Imagery

Vision is the primary source of information about the environment. The eyes of humans and of most animals are sensitive to visible light, which consists of a very narrow portion of the electromagnetic spectrum. As a result, the ability to see depends on reflected or emitted light that reaches the eye. When there is no light (e.g., at night) or when the light is absorbed or scattered before it reaches the eye (e.g., during fog) or when an object is concealed by another object which does not transmit light (e.g., camouflage), then the ability to see is degraded.

Various devices have been developed to transform information that is contained in other bands of electromagnetic radiation into visible representations. Well-known examples are X-rays, radar (radio wavelength) and FLIR (typically thermal) imaging. Some of these techniques are active i.e., radiation is artificially emitted and then recorded (e.g., X-ray, radar); and some are passive i.e., natural radiation is captured by sensors (e.g., FLIR imaging, light amplification, multi-spectral).

The visual images that are produced for display to a human operator or analyst by most of these techniques differ distinctly from regular, visual band images. In regular monochrome images (e.g., black and white television [TV]), the distribution of gray shades represents the relative brightness and reflectance of objects in the scene. Usually, the resulting image seems "natural" i.e., it is similar to what the eye is accustomed to seeing in everyday life. In other types of sensor imagery the distribution of gray shades in the image represents different phenomena. As a result, these images appear significantly different from regular images of the same scene and also, from each other. Therefore, the interpretation of each type requires special skills. The special nature of FLIR and SAR imagery is discussed in more detail below.

FLIR Imagery

Capturing electromagnetic radiation in the IR band and transforming it into visible images creates FLIR imagery. Every object, whose temperature is above absolute zero, emits electromagnetic radiation. The spectral range and the intensity in which most radiation is emitted depend on the temperature and the emissivity (emission efficiency) of the object. The radiant emittance from the surface of the earth is similar to the emittance of a blackbody at 300 degrees K. It is near zero in the visible band and reaches its peak around 10 microns. This range is loosely defined as the IR band. Typically, FLIR systems operate either in the 3 – 5 micron band, or in the 8 – 12 micron band, in which there is good atmospheric transmission. The background contrast is typically higher in the 8 – 12 micron band, resulting in a more distinct representation of image details (i.e., better image quality).

Images in the natural visual spectrum (0.4 – 0.7 microns) consist of light that is provided by one remote source (sun, moon) and reflected from features in the environment. The brightness of any given point in the environment depends on the reflection of source light incident on that point. Most terrestrial materials have good reflectance in the visible band. Conversely, only an insignificant portion of incident infrared radiation is reflected. Therefore, FLIR images are produced primarily by emitted IR radiation. In other words, while regular images depend on the immediate presence of a light source, the thermal image represents the "memory" of previously accumulated energy (and self-generated heat), and does not depend on the immediate presence of an external source of energy. As a result, thermal images are capable of extending human vision into the night. In addition, infrared radiation is less affected than light by small atmospheric particles and, to some extent, may penetrate through smoke, haze and fog. It may also penetrate some sorts of materials and "see" hot

objects (e.g., engines) through camouflage. FLIR systems are used as night vision devices on many different types of platforms (e.g., fighter aircraft, helicopters, remotely piloted and unmanned air vehicles, guided missiles, tank and armored vehicles) and for a variety of applications (reconnaissance, navigation, night flight, night driving, target acquisition).

The dynamic temperature range that IR detectors are capable of handling is usually much too large to be usefully displayed at once. For example, the temperature range between a "hot" target (e.g., an aircraft) and a "cold" background (e.g., the sky), may span more than 300 degrees C and the IR detector may be able to sense temperature differences of less than 0.5 degrees. Therefore, FLIR systems are provided with level-control that sets the range of temperatures to be displayed, and gain-control that determines the gray shade mapping of temperatures within that range. In addition, most FLIR systems can control polarity, i.e., the way in which gray shades represent temperatures. Polarity may be set to "black hot" depicting hot objects as dark gray shades and cold objects as bright gray shades or it may be set to the opposite, "white hot".

FLIR images differ significantly from regular (i.e., visual) images (Brickner and Zvuloni, 1993).

The distribution of gray shades in the FLIR image represents the mapping of relative IR emittance of objects in the scene (determined by objects' temperatures and emissivity) and not their brightness and reflectance. The IR image is created by emitted rather than reflected light and therefore, lacks the systematic shading characteristic of daytime natural scenes.

Regular images and IR images change over time in different ways. Regular images tend to change gradually and systematically (e.g., the brightness of the whole image is reduced and all shadows grow longer towards dusk). IR images change in a much less predictable manner because the relative heat emittance of objects in the scene may rapidly change and even reverse (e.g., metal objects, which absorb and emit heat rapidly, seem hot during the day but cool off rapidly during the night). Furthermore, when the heat emittance of an object is close to that of the background (the "crossover" point) it may become invisible.

Human-made and natural sources of heat (e.g., fire, friction, chemical processes) may create unique thermal signatures that are significantly different from the regular representation of the same objects.

SAR Imagery

SAR is a coherent radar system located on a moving platform. The radar transmits a narrow pulse of electromagnetic energy, which is reflected from the area on the ground and is returned to a receiver. The synthetic aperture is formed as the physical antenna (installed on an aircraft or satellite) moves through space. The image

formation is usually based on the assumption that only a linear motion of constant velocity is present. SAR requires motion compensation to remove the effects of other motion. The aircraft motion is acquired from the inertial navigation system. Then the receiver local oscillator (LO) is offset by an appropriate frequency to remove the instantaneous line-of-sight Doppler component (due to the aircraft motion) from the radar signal.

SAR offers two compelling advantages over conventional (electro-optical) sensing technologies: standoff range and adverse weather capabilities. SAR images can be formed with effectively no loss in resolution up to the limits of the system's stabilization and motion compensation capabilities. SAR sensors can "see" through clouds and through light rain. Further, depending on their coverage mode and data processing limitations, SAR sensors can be capable of high area coverage rates. These attributes make SAR imaging a valuable resource for tactical and theater airborne reconnaissance, surveillance and target acquisition applications.

SAR, however, is a non-literal imaging sensor, that is, the imagery produced by a SAR does not resemble a photograph taken of the same scene. The intensity values in the SAR image are proportional to the radar cross sections (RCS) of the corresponding points in the ground scene (and not to their visible wavelength reflectance). The impulse response function of the SAR (the fundamental determinant of system resolution) includes side lobes. Thus, the return from a point on the ground may include energy contributed by adjacent scatterers. In addition, high order acceleration deviations of the moving platform, from the computed virtual antenna, may contribute visual noise.

The "shadows" in a SAR image are caused by the active illumination of the scene by the transmitting radar (and not by the sun angle). If the grazing angle is low and the area mountainous, large areas may be concealed from radiation and appear as black. The perspective of a SAR image is that of an observer looking down on to the scene from directly above, as the radar illuminates it from one side.

SAR images appear very different from both regular and FLIR images in other ways as well.

The distribution of gray shades in the SAR image represent the proportional RCS of the corresponding points in the ground scene, as "viewed" by the radar receiver, and is not correlated with gray shade distribution of regular images or FLIR images.

Unlike regular imagery (e.g. TV) and FLIR imagery, SAR images are not affected by time-of-day and are only marginally affected by atmospheric conditions.

SAR imagery is strongly affected by the transmission angle of the radar, which changes the effective RCS of objects in the scene and their appearance on the display.

Until recently, most operational SAR systems provided much lower resolution than TV and FLIR systems. These low-resolution SAR images presented very crude images of the world that could be interpreted only by pattern (e.g., SAM3 site) or by reference to other information sources (e.g., detecting changes between a new image and a previously interpreted one). Recently, high-resolution SAR systems are becoming available. These systems may allow the recognition of objects with sufficiently large RCS and distinct contour lines (e.g., roads, buildings, military vehicles).

SECTION II

SIMULATION OF SENSOR IMAGERY

Real sensor imagery is acquired and recorded during real-world missions. Obviously, the use of a real system for non-operational purposes is rather costly and limited. Furthermore, the collection of actual imagery to meet the requirements of methodical training or of an experimental design (different grazing angles, target orientation, etc.) may be too complicated and expensive to achieve with sufficiently accurate control over the parameters of interest. Therefore, there is a strong need for simulated sensor imagery.

Uses of simulated sensor imagery

Simulated sensor imagery may serve various different purposes:

Operator training and mission rehearsal

General (procedural) training: Incorporating sensor imagery into a simulated environment (e.g., flight simulators) where sensor imagery is not the primary goal of training but rather part of the operating procedure (e.g., general pilot training).

Specific training: Training of sensor imagery operators (e.g., SAR imagery analysts, FLIR weapon system operators).

Mission planning and rehearsal: If a mission environment can be simulated, the operator may use it to plan the mission and gain effective rehearsal of the mission.

System research and development

Sensor system design.

Sensor system analysis.

Sensor performance analysis and evaluation.

Automatic target recognition (ATR) development, research and training.

Human factors studies

Operator performance studies

Imagery exploitation

Predictions of what a target should look like, to be used in comparison with actual sensor imagery.

Generation and evaluation of softcopy imagery interpretation key materials for use by imagery analysts.

Types of simulation systems

Over the years, various approaches to sensor imagery simulation have been developed, based on existing technological capabilities. Bair (1996) described the evolution of airborne A/G (air to ground) radar simulation (DRLMS – Digital Radar Landmass Simulation). In the mid 1960's glass plates with flying spot scanners were used to generate simulated radar displays. Terrain boards were used in the 1970's. Neither of these methods produced accurate depictions of angle or resolution effects. Another difficulty with early DRLMS was the lack of adequate source data from which to build the landmass database. This problem was abated in the early 1970's with the introduction of digital mapping systems that eventually led to the modern Digital Terrain Elevation Data (DTED) and Digital Feature Analysis Data (DFAD). By 1980, hardware-intensive implementations of radar models were constructed. These were big, expensive and hard-to-maintain devices. In 1985 a software-only solution was developed, based on large mainframe computers. This led to the use of UNIX based workstations which are still in extensive use. Recently, some PC based solutions have also become available (e.g., RadBase).

A similar but somewhat different trend can be identified in FLIR simulations. A model board with heated metal objects representing targets was used at the US Army Night Vision Laboratory in the 1970's. Recorded sensor imagery was used as a substitute for real imagery in many early studies (e.g., Mocharnuk, Gaudio and Suwe, 1981). Recorded images were used to create "closed loop" simulations by recording the images on video disk and providing a limited level of interactive dynamics. In addition, various image processing functions could be used to manipulate the image, and simulate gain, level, polarity etc. (e.g., Brickner and Foyle, 1995). Image processing techniques have been used to make daytime images look similar to sensor imagery. For example, some aircraft and rotorcraft simulators have image-processing capabilities for the out-of-the-window (OTW) view, that simulate light intensification, FLIR or Radar images (e.g., De Maio and Baker, 1994).

Various hybrid methods have also been used. For example, in FLIR simulation, some systems have combined a low-fidelity, image processed background, with high-fidelity recordings or physical models of targets (e.g., De Maio and Baker).

Physics based simulation tools are the state-of-the-art in both radar and FLIR simulation. These systems use digital models of the real environment (terrain, atmosphere), the sensor system (e.g., a specific FLIR) and implement parameters and equations of the real world (e.g., the physics of radiation) (Blasband and Jafolla, 1999). A comprehensive, critical review of physics-based simulation systems is presented in the next section.

SECTION III

PHYSICS-BASED SIMULATION SYSTEMS

Sensor simulation tools have developed, gradually, along with technological capabilities. Powerful computers and 3D graphics tools, enable the formation of precise and detailed simulations. Most advanced are recent physics-based simulation tools that model the components that impact real sensor images: the environment (terrain and atmosphere), the radiometric equations, and the sensor system. A survey was conducted to identify existing sensor imagery simulation products and applications. The following critical review of physics-based simulation tools is composed primarily of a group of simulation tools built by or in collaboration with: MultiGen-Paradigm (MP), Surface Optics Corporation (SOC), and Photon Research associates (PRA). Other simulation tools, built by Technology Service Corporation (TSC), and by Camber Corporation, will be mentioned briefly. The written references to these simulation tools are either technical papers or the companies' web sites:

RadarWorks™ (MP) - A physics-based simulation tool, for different types of imaging radars. It is comprised of two main software components. The first component (Radar Vision), generates a pixelized RCS map of the desired area, in units of dBsm, in real-time. The second component (the sensor model), models the specific radar device (Blasband, Jorch, & Sigda, 1998).

Camber Radar Toolkit™ (Camber Corporation) - A comprehensive real-time radar simulation. Provides a complex, real world, energy level model of the interaction of the emitted radio transmissions and the simulated environment (<http://www.cambertx.com/RTK.html>).

RadBase™ (SOC) - A physics-based radar database generation tool. Calculates accurate RCS and Amplitude & Phase data for complex targets and cultural features, using a hybrid geometrical/physical optics approach. RadBase has been validated against range measurements (Blasband & Jafolla, 1999).

XPATCH (developed for the US government by DEMACO [now SAIC]) - An electromagnetic computer prediction code for generating RCS, time domain signatures and SAR images of realistic 3-D vehicles (Andersh, Lee & Ling *see* <http://www.demaco.com/papers/sbr1/>).

SensorVision™ (MP) - A real-time physics-based simulation of electro-optical sensor imaging (visible through far infrared). Produces a sensor spectral response (Anding, 1998).

SensorWorks™ (PRA) - Adds realistic sensor effects to the SensorVision image (McGlamery, Johnson & Scully, 1998).

IRGen® (TSC) - creates an IR database as viewed by a thermal IR sensor, using first-principles models of heat transport, radiation, and sensor processing (Technology Service Corporation, 1996).

Physics-based simulations consist of many components, each of which may affect the final quality of the simulation. The major components are discussed below.

Modeling of the environment - Database construction

A digital model of natural terrain and of man-made objects on the terrain is the first component of the simulation. The model serves as an input database for the simulation tools. Tools for building digital models (e.g., MultiGen Creator) enable the user to go to almost any desired level of detail. Obviously, the level of detail may affect the quality of the resulting sensor simulation. Hence, the decision as to how much effort should be invested in the digital terrain/object modeling phase may impact the final results.

The first stage in building a digital model of a scene is modeling the structure the terrain, with pixels or polygons. Often, a model of a real terrain is most desirable. Using aerial photographs and elevation data, precise modeling of terrain can be achieved. One major drawback of such models is that most man-made objects do not have associated height/elevation data. Hence, they appear two-dimensional and, without special treatment, they cannot be treated as objects in the simulation. One should also bear in mind that the resolution of the source (e.g., aerial photograph) poses an upper limit to the resolution of the sensor image. For example, a satellite terrain photograph of 10m/pixel cannot provide higher than 10m/pixel details of the terrain (in practice, as low as 20m/pixel).

Sensor imagery simulation requires not only the structure but also the material map of the terrain and the terrain-objects. As will be shown and discussed (in following sections), this information is crucial for the types of simulation discussed in the present document.

All the above simulation models use polygons as basic building blocks for terrain and objects. Polygons can be assigned different properties, like color and texture, which can make them look similar to real-world objects to the naked eye. However, in order to simulate different sensors, additional properties, may be needed. Hence, the next stage is to assign polygons with relevant and meaningful properties. When dealing with SAR and FLIR, the important properties relate to materials and their characteristics, e.g., reflectivity, heat emittance properties, etc.

When simulating the visual band, it may sometimes be possible to “save” polygons and use texture as a substitute (e.g., a building may be represented by as few as six polygons, with textures (of bricks, windows, doors, etc.) added to increase “detail” and “realism.” However, for sensor imagery, polygons should be specified in accordance with material boundaries. It may not be satisfactory in this case to use fewer polygons, while “compensating” with textures.

SensorVision™

SensorVision™ is a real-time physics-based simulation program tool for electro-optical sensor imaging (visible through far infrared). It produces a sensor spectral response of both out-the-window (OTW) displays of a synthetic environment and correlated sensor views of these environments.

For high-fidelity results of the simulation, the database for the SensorVision™ simulation tool must provide an accurate representation of reality. In some cases it may be required to represent some specific terrain, while in others, it may suffice to provide a seemingly “realistic” terrain. Polygon representation must be at an adequate level of detail to represent slopes of surfaces and material boundaries. Reflectance and thermo-physical parameter values for all surfaces must be accurate representations, and the atmospheric state must be well defined. The synthetic environment can include digitized natural terrain backgrounds, cultural objects, mobile objects and atmospheric states that are homogeneous in the horizontal dimension.

In conjunction with SensorVision™, two database construction tools can be used in the pre-process mode, to prepare relevant inputs to the application:

Texture Material Mapper™ (TMM)

Generates textures of material codes and radiance, by transforming RGB colors or intensities to linear combinations of materials. The user transforms all scene database textures into the material codes needed for the simulation, mapping visual color spots to materials, and indicating the substance each colored spot represents. TMM™ includes only a sample of materials, but it can be expanded by the user. The user has the responsibility to generate a relevant and valid database. Reflectance quantities are derived from the materials database, which represents the most commonly occurring measurable case, for each material. It is important to insert correct values into the database: either valid measured data, or representative data, depending on the user’s needs and on the availability of data.

MOSART Atmospheric Tool™ (MAT)

Generates material surface temperatures and atmospheric quantities, according to parameters chosen by the user (latitude, longitude, date and weather) and the simulated-sensor spectral response function. Thermal quantity (radiance

parameters) is derived from the material surface database. MAT does not provide accurate representations of high vertical vegetation (e.g., trees) or heat generators (e.g., operated vehicles), and does not handle water, ice and snow.

From geometric considerations, SensorVision™ when applied to high-fidelity databases, can provide accurate and valid radiance images. When applied to databases with fewer details than the pixel resolution and spectral response of the simulated sensor, simulation fidelity is compromised. SensorVision™ provides the user with complete control over the desired level of details, and over database construction. In practice, however, the user may not have access to sufficiently detailed information and may not be able to reach the desired level of simulation fidelity.

IRGen®

As in SensorVision™, each polygon in the data base of IRGen® has to be labeled with a material code, which specifies the properties of that surface. The material code is then used by the thermal model to compute surface temperature and radiance. In addition, an environment model contains the parameters, which specify the thermal environment of the database.

RadarWorks™

The physics-based approach for imaging radar simulations, maps scene materials to RCS (Radar Cross Section) values. The synthetic environment is a 3-D polygonal database with RGB textures. RadarWorks™, like SensorVision™, uses the TMM™ to generate material-coded textures from visual database RGB textures.

RadBase™

RadBase™ is designed to primarily for creating detailed and accurate models of 3D objects. The input to RadBase™ is a 3-D wireframe model of the object to be simulated. Like the other simulation inputs described above, materials have to be mapped to the object parts.

Modeling of the physics

Once a terrain, objects and environment model has been set, the physics-based simulation system subjects it to radiometric equations, according to the simulated sensor (e.g., heat emission equations for FLIR; electromagnetic scattering equations for SAR).

SensorVision™

SensorVision™ evaluates a radiometric equation during the visualization process, for each pixel of every image frame, taking into account the input databases. The output

is line-of-sight radiance, expressed in absolute radiometric units (watts/cm²/sr), for each pixel of the image.

Users can configure the radiometric equation to use any of the following components:

1. Diffuse solar and lunar reflections
2. Specular reflections
3. Ambient sky-shine reflections
4. Thermal emissions
5. Path emission
6. Scattering
- 7.

Effects report as being added in the future include:

1. Shadows (reflective or thermal)
2. Luminosity reflections (sun/moon and sky)
3. Bi-directional reflection (diffuse and specular component)

The process can be run in real-time, and can accommodate dynamic changes to the environment or the view perspective.

Most terrestrial materials are very diffuse. For them, the equation is a good approximation.

IRGen®

Given a user-specified thermal environment, IRGen® computes the surface temperature of every polygon in the database. This is a first-principles calculation using the time-dependent heat transport equation, integrated with a finite-difference time-dependent solution method. IRGen® has accurate models for exterior and interior heat sources for each surface.

The thermal model computes the surface radiance from the surface temperature, emissivity, and reflected radiance terms. The radiance is computed in the sensor spectral band, and later serves as the input to the sensor model.

RadarWorks™

The RadarVision™ module of RadarWorks™ maps scene materials to RCS values, taking into consideration different parameters determined by the user:

1. Frequency range (1-27GHz)
2. Linear polarization
3. Ground squint angle
4. Radar incident angle

5. Pixel resolution

RCS values are obtained from a database, and through interpolations.

RadarWorks™ uses two databases. The first is a database of natural terrain mean-backscatter-coefficients, which was generated from validated measures, using many different radar parameters. The second is a database of RCS values for cultural features, as a function of frequency, polarization and geometry. The primary databases are limited, but can be expanded by the user.

RCS values are affected by material information (derived from the database built with the TMM™ - [see above]), radar/polygon geometry (incident angle and azimuth angle) and radar parameters.

Radar shadows are computed in real-time, according to the radar/polygon geometry.

RadBase™

RadBase™ calculates RCS values as a function of frequency, polarization and target/observer geometry (incident angle and azimuth angle), using the physical optics (PO) approach approximation to electromagnetic scattering.

PO theory is based upon source currents, and is valid in cases where the incident wavelength is much smaller than the length of the object scattering the energy. It uses the integral equation representation for the scattered fields. It relies on the high frequency assumption that the scattered field, from one point on an object to any other point, is negligible compared to the incident field. Hence, the total field at each point on the surface of the object is approximately equal to the incident field at that point. Thus, the equation that has to be solved is much simplified.

RadBase™ includes the following physical phenomena: blocking, multiple-bounce interaction, edge diffraction, polarization, dielectric materials and bi-static computations.

The calculations of RadBase™ are based on the model that serves as input, and on other parameters determined by the user:

1. Multiple bounces: the number of multiple bounces off the object that the radar beam can undergo before returning to the receiver - currently, up to two bounces are enabled.
2. Blocking: refers to one facet of the target vehicle blocking another facet from the radar view.
3. Edge diffraction: Edge effects can have significant effect on the RCS of complex objects. RadBase™ enables the user to select whether or not to compute edge diffraction.
4. Maximum Interior Wedge Angle - defines the maximum angle at

which two facets form an edge. This prevents inclusion of edges in which the interior angle is close to 180 degrees.

5. Frequencies: the frequencies (GHz) for which the RCS is computed.
6. Elevation angles: the elevation angles (degrees) for which the RCS is computed.
7. Azimuth angles: the azimuth angles (degrees) for which the RCS is computed.

The output is a file that contains RCS data for all the pre-defined frequencies, two polarizations, and pre-defined elevation and azimuth angles. (A different file contains the amplitude and phase data). It can be used as input to other simulation tools, like RadarWorks, to obtain a precise simulation of both the terrain and the cultural features.

XPATCH

The XPATCH computer code, based on the shooting and bouncing ray technique, is used to calculate the polarimetric radar return from complex geometric shapes represented by CAD (computer aided design) files. The first-bounce Physical Optics, the Physical Theory of Diffraction, and the multi-bounce geometric optic ray contributions are included in the equation. XPATCH doesn't currently perform calculations for some of the high order scattering effects (traveling and creeping waves, surface waves and resonant effects).

Modeling of the sensor system

The images that are formed by implementing valid physical equations to valid digital models are "perfect" sensor images. Perfect, in the sense that their quality has not yet been diminished by the sensor itself. Sensor systems introduce noise and other effects to the image, and are bound to modify its appearance.

SensorWorks™

SensorWorks™ provides the capability to add realistic sensor effects to SensorVision™ images. The outcomes reflect the effects of specific electro-optical (EO) sensors, rather than an OTW view.

In a basic EO sensor system, there are four main subsystems, each of which may affect the output image of the sensor:

Optical system: Collects light from the scene, and forms an image at the focal plane. Design and manufacturing errors, which can cause the image at the focal plane to be blurred, and diffraction blur effects, can be modeled.

Focal Plane Array (FPA): An array of one or more detectors, which spatially sample the energy in the scene and convert it into a signal. A single detector channel scans the scene in a raster fashion. A linear array of detectors scans the

image in one direction, and a two-dimensional array of detectors samples the scene without scanning. Spectral response, detector responsivity, offset, noise and optical blur, which are produced by the FPA, can be modeled. SensorWorks™ does not as accurately model detector response non-linearities and blooming.

Signal processor: Converts the signal to a useable electronic form. For purposes of simulation, the signal processor can usually be disregarded. However, the DC restoration and non-uniformity correction processes, if significant, should (and can) be modeled.

Display system: Generates and displays an image of the converted signal. The display has a modulation transfer function, signal transfer function and non-linearity, which add to the system noise that can be modeled. **Operator controls** for the display usually add random LOS errors (drift and jitter), that can be modeled. Moreover, the operator may be able to control the line-of-sight of the sensor and its gain and offset settings.

Sensor platforms can effect the sensor image by motion and vibration. Low frequency motion causes jitter, which can be modeled. High frequency motion causes blur, which isn't modeled by SensorWorks™.

A large number of individual effects can be combined as needed to simulate the characteristics of a wide variety of sensors. SensorWorks™ supports the following effects:

Jitter – due to platform motion.

Blur (Convolution) - due to optical-system and integration of the scene by each sensor detector-element over the area of the element.

Sub-sampling (Zoom-in) - depending on the sensor.

Saturation Radiance - only the hard saturation is modeled (saturation is a non-linearity of response to input flux, and can be either soft or hard).

Responsivity Variations - optical sensors have pixel-to-pixel variations in responsivity. The arrays can be customized to represent different sensors.

Offset Variations - for either intrinsic offsets or the residual offsets after the non-uniformity correction (NUC) process.

Sensor Noise - photon and electronic noise. A single noise type represents the different individual noises. Temporally varying random noise is produced.

Contrast Control (gain and offset) - manual, auto and dynamic range.

White hot / Black hot - the polarity of the contrast can be inverted.

Zoom-out - to increase the image size for display purposes.

Display color - for simulating display systems with a single color output.

IRGen®

The sensor model contains the parameters, which specify the properties of the simulated sensor. Sets of sensor parameters can be stored and saved. The user-specified sensor parameters include spectral band, spectral response, display dynamic

range, and white hot / black hot modes.

RadarWorks™

The RCS map, which is the output of the RadarVision™ module, serves as input to a radar sensor model. The output is presented on a Plan Position Indicator (PPI) or a raster display - depending on the radar mode being simulated.

The user selects the type of radar, and indicates important radar parameters, frequency and polarization effect the RCS map.

The sensor model generates a radar display by combining the RCS map with the user-defined values for radar parameters (e.g., ground squint angle, radar incidence angle).

RadarWorks provides several radar modes, one of which is **SAR**. The SAR mode uses the RCS map, which represents a “perfect” SAR image, as input. The output is a modified RCS map that manifests several sensor and processing effects of the SAR.

Motion compensation: Poor motion compensation causes smearing of objects in the image. The amount of smearing depends on the quality of the mathematical calculations. The SAR model provides four levels of motion compensation.

Frequency agility: Radar returns from object in a scene are affected by the radar frequency (scintillation). Hence, at certain frequencies, a single pixel may appear brighter than nearby pixels of the same material. Recurring looks at the scene, in different frequencies (known as frequency agility), averages this effect and minimizes the speckle. The SAR model can model both scintillation and frequency agility.

SAR mode: Synthetic aperture radar systems usually operate in one of two modes, a strip mode (successive images of the ground), or a spotlight mode (higher resolution as a result of longer integration times). RadarWorks™ is currently restricted to modeling the strip mode.

The output of the SAR mode depends on several user-defined parameters:

1. Range to center of map
2. Squint angle
3. Map size
4. Resolution method:
 - The user defines resolution in meters/pixel, or
 - The user defines FFT and PRF and RadarWorks computes the pixel resolution
5. Motion compensation
6. Frequency agility
7. Nominal aircraft speed

SECTION IV

SIMULATION FIDELITY: TRANSFER OF EXPERIENCE AND OBJECT PERCEPTION

In this section we present and discuss the concepts of “simulation fidelity”, “transfer of experience”, “object / pattern recognition” and some related topics. These concepts are used, in the next sections, to analyze simulated sensor imagery.

Simulation Fidelity

The concept “simulation fidelity” is used to describe the effective differences between a real and a simulated system. Ideally the simulated image should be identical to its real world counterpart (i.e., perfect simulation fidelity). However, perfect simulations may not be feasible (technically or financially) and may not always be necessary (a central issue of the present study), therefore, compromises have to be made.

Ehret, Gray and Kirshenbaum (2000) presented the concept of *scaled worlds* in the context of field research. Based on Brehmer and Dörner (1993) their basic supposition is that real field situations are too complex for investigation and do not allow definite conclusion, whereas, in laboratory studies there may be too little complexity to allow interesting conclusions. Hence various methods of simulation have to be developed to bridge between the worlds. We suggest that the relevance of these concepts extends beyond the context of field research and propose to use them in the analysis of other situations in which a real world is represented by some sort of simulation. In addition to scaled worlds, in which scaling is based on a cognitive task analysis, it is possible to use high-fidelity simulations, synthetic environments and microworlds. Three dimensions are proposed in order to analyze the differences between these types of simulations: *tractability*, *realism* and *engagement*.

Tractability examines whether the user or the simulation can pursue the questions of interest (i.e., research, training, etc.). Tractability is a relative dimension defined by the question at hand. The simulated task is realistic to the extent that experiences encountered in the simulated environment occur in the real world task environment. Engagement describes something about users' motivation, e.g., is the simulation interesting, challenging, etc. This dimension may be relevant to the extent that experts are often reluctant to use low-fidelity simulation regardless of its purpose and relevance.

Various approaches can be used to estimate the magnitude of differences between a real and a simulated image (i.e., simulation fidelity). Three such approaches are discussed below.

Visual discrimination

A simple and straightforward approach is to use a measure of differences between real and simulated images of the same scene. The Sarnoff Visual Discrimination Model (VDM - Lubin, 1995) offers an advanced technique for such a comparison. VDM simulates human vision mechanisms for discrimination between similar images and provides a quantitative rating for the differences. The model is designed to compare pairs of images. The input to the model is a pair of images and the output is a map showing the probability that an observer would be able to detect the differences between the images. The differences may be presented as a JND (just noticeable difference) map, in which the high gray levels correspond to high probabilities of discrimination by a human observer and *vice versa*. The actual probability values on the JND-maps are calibrated in terms of JNDs. JND=1 corresponds to a 75% probability that a human observer viewing the two images multiple times would be able to see the differences; JND=2 corresponds to 93.75 probability; JND=3 to 98.44, etc. For example, Brickner, Silbiger and Lubin, (1998), investigated the differences between original and compressed sensor images. The threshold of discrimination between compressed and uncompressed images was determined in a well-controlled psychophysical experiment. It was argued that image compression levels, which are below discrimination threshold, could be used without consequences on operator performance. If such a comparison would have been made between a real and a simulated image of the same scene, a below-discrimination threshold difference between the images could be interpreted as "perfect simulation fidelity."

The VDM approach has two major drawbacks. First, it can only be applied to images that can be compared pixel-by-pixel. Second, the result of such a comparison is a number that indicates the magnitude, but not the significance, of the differences. Clearly, below threshold differences between real and simulated images indicate very high fidelity. However, perfect fidelity is rarely required and almost never feasible and the model does not say much about the significance of larger (i.e., super-threshold) differences. Furthermore, similar JND numbers may stem from different types of differences between images and have different effects on operators' performance.

Mathematical models of detection, recognition and identification

Mathematical models of target detection, recognition and identification have been developed for both applied (e.g., ATR; Ross, Bradley, Hudson and O'Connor, 1999; Boshra and Bhanu, 1999) and theoretical purposes (e.g., Sheffer and Ingman, 1997). For example Sheffer and Ingman (1997) developed a model for analyzing tasks involving target acquisition. Their model included target detection, recognition and identification thresholds and predicting the functional, parametric dependencies of the results of observation experiments by human observers. An image of a certain scene was treated as a sample of an entire set of images of that particular scene. A difference measure called the Information Difference (InDif) between two image sets was defined. It was argued that accomplishing target recognition tasks is equivalent to setting thresholds for the InDif. The applicability of InDif to the performance of the

human visual system was shown both analytically and in computer calculations of noisy images.

It can be argued that such measures could be used to express the "similarity" between real and simulated images. If an simulated image of a scene can be shown to represent a set of real images of a similar scene, then we may assume a certain level of fidelity of the simulated image. Presently, this argument is purely speculative because the model has been applied to different kinds of issues and has not been validated for this type of problem.

Transfer of experience

A more viable approach to the evaluation of sensor-imagery simulation-fidelity is, to identify possible differences between real and simulated images and to analyze them in terms of the specific objectives of the simulation.

This approach leads to the concept of "transfer of experience" (we chose to use this generic term rather than the more common "transfer of training" because simulation may be used for purposes other than training). The question is to what extent experience with a simulated system is equivalent to similar experience with a real system. In simulator training, transfer of experience was quantified (e.g., Roscoe, 1971). Perfect transfer means that one hour of experience with the simulated system is equivalent to one hour with the real system; fifty-percent transfer means that two hours with the simulation are equivalent to one hour with the real system, etc. Negative transfer means that experience with the simulation produced worse results on real system performance, than no experience at all. In other environments (i.e., system research and development, human factors studies and imagery exploitation), transfer of experience requires specific definitions and is more difficult to measure. These issues are discussed below.

Pattern and object recognition

Less-than-perfect simulation fidelity means that the features of some patterns or objects in the simulated scene are represented differently than in the real scene. In order to understand these differences it is necessary to understand the mental processes of object recognition. Pattern and object recognition is a mental process during which a perceived stimulus is matched with a corresponding internal, mental representation.

Psychological theories of object recognition may be classified under four broad headings: template theories, prototype theories, feature theories, and structure-description theories, all of which are classified as "bottom-up" approaches. In addition, "top-down" theories, that emphasize the effects of context on perception, will be mentioned. Distributed representation and connectionism will be discussed briefly. Mathematical model for object detection, recognition and identification have been discussed briefly in section "Mathematical models of detection, recognition and identification" above.

Template theories argue that pattern recognition involves matching sensory inputs against specific, labeled, template-like representations stored in memory (Neisser, 1967).

Template theories were rejected at an early stage, because they failed to explain some basic aspects of human perception, e.g., the ability to recognize a huge variety of objects from many different angles, lighting conditions, etc.

The rigidity of template theories led to an alternative explanation: prototype-matching theory. Prototype theory argues that the basic elements of a pattern class are abstract memory representations called *prototypes*. A prototype is characterized as a synthesis or a statistical average of all the individual patterns belonging to a category (Rosch, 1973). Feature theories postulate that the visual system analyses and represents sensory information in abstract, primitive information units called features or attributes; a "distinctive feature" can be used to make a critical distinction between patterns or classes of objects (e.g., Gibson, 1969). The recognition of a pattern involves the analysis of its features (e.g., line direction, size, color, etc.). Feature theories received strong reinforcement from neurological studies which identified brain cells sensitive to lines of a specific orientation (Hubel and Wiesel, 1963, 1968) corners and angles (DeValois and DeValois, 1980). In addition, highly sophisticated complex cells that respond to specific complex shapes (e.g., hand or face) were discovered (Shapley and Lennie, 1985). Biederman (1987) hypothesized a means by which stable, three-dimensional mental representation of objects, can be based on simple geometric shapes he called *geons*". According to Biederman's recognition-by-component theory, objects are recognized by observing their edges and then decomposing them into *geons*, which can then be recomposed into alternative arrangements.

The aforementioned theoretical approaches may be characterized as bottom-up theories that interpret perception as driven by the data that constitutes the pattern. These theories do not fully explain context effects. Fairly dramatic context effects have been demonstrated by Gestalt theory and more recently by many other researchers (e.g., Pomerantz, 1981). Ullman (1989) classified the different paths leading to object recognition into those that are primarily visual and those that are supplemented by other sources. Other researchers argued that objects may be recognized on the basis of their visual features, such as characteristic shape (Biederman, 1987); color, texture, location, typical motion (Cutting and Kozlowsky, 1977); and also on the basis of prior knowledge, reasoning, expectations and continuity of events (Palmer, 1975).

All the above theories represent symbolic approaches to mental representation. Their basic view is that human cognition is centrally dependent on the manipulation of symbolic representations by various rule-based processes. The connectionist approach proposes an alternative view. Connectionist schemes can represent information without recourse to symbolic entities like propositions; they are said to represent information sub-symbolically in distributed representations (Smolensky, 1988). Without having to use large sets of explicit propositional rules they have the potential to model complex behavior. (e.g., Rumelhart, McClelland and the PDP research group, 1985). A distributed representation does not have symbols that represent an object explicitly but rather stores the connection strengths between units that will allow sight of the object to be recreated. Input cells take signals from vision (vision units), a neural network associates the pattern of activation that arrives at the various vision units. The distributed representation of the

sight of the object is thus represented by a matrix of activation over the units in the network, without recourse to any explicit symbol for representing that particular object.

The exposure to stimuli leaves "memory traces" that activate various neural units. The connections between units provide the "representation" of a pattern or an object. These connections are strengthened through repeated exposure and weakened during periods of no exposure. As a result, objects and patterns that have strong, well-established connections in memory are recognized rapidly and accurately, whereas weak or inappropriate connections lead to slow and inaccurate recognition. In other words, transfer of experience from a simulated image to a real one, depends on the strength of connections that developed during exposure to simulated images. Strong, well-established connections result in high transfer, poor connections result in low transfer and irrelevant or wrong connections may result in negative transfer of experience.

Object recognition in real-life situations

The mental representation of patterns and objects is a theoretical construct that cannot be measured directly and has to be deduced from behavior. We suggest that whenever possible, the performance of pattern / object detection, recognition and identification may serve as a useful behavioral measure. The latest version of the vision model of MIDAS - the computerized human performance model (Shively, Burdick, Brickner and Silbiger, in preparation), classifies the features of each object according to their relative contribution to detection, recognition and identification. According to the model, detection is affected primarily by object-to-background contrast, movement, motion (movement of internal parts) and size. Recognition and identification are affected primarily by shape (contour lines), size, movement and motion, location, color and texture.

A simulated pattern or object may deviate from a real object in any of these features, thereby affecting its perception. The effects of such deviations on transfer-of-experience depend on the nature and the purpose of simulation. For examples, contour lines are a major determinant in object recognition (Biederman, 1987; Ullman, 1989), hence, low-fidelity representation of contour lines may affect object recognition. False representation of contour lines may lead to poor or even negative transfer of experience. For example, if the simulated contour lines are more salient than the real ones, the operator may be led to faultily expect easy recognition of objects.

Brickner and Zvuloni, (1993) investigated the preferred polarity in FLIR object recognition tasks. They found that there is no one preferred polarity, rather, some objects are more readily recognized in black-hot, some are easier to recognize in white-hot, while other seem to be insensitive. The researchers determined that objects are easier to recognize when their presentation is similar to their expected regular (visual band) images (e.g., it is easier to recognize trees as dark objects on a light background rather than the other way round). These conclusions may also be generalized to simulated images. Positive transfer of experience may occur when the expectations, generated by the simulated image are met in the real world and *vice versa*.

Maayan (1989), investigated target recognition in low quality FLIR images. Based on Biederman's (1987) object recognition theory, Maayan argued that whereas objects in the visual band are recognized primarily by their contour lines, the recognition of objects in the IR band (FLIR) relies heavily on surface determinants (texture and internal contrasts).

SECTION V

SOURCES OF DEVIATION BETWEEN REAL AND SIMULATED IMAGES

In this section, potential deviations between real and simulated images are analyzed. The analysis refers to state-of-the-art, physics-based simulation models. In such models, fidelity deviations may stem either from the input to the model (i.e., databases and parameters) or from the computations of the model itself. As shown below, state-of-the-art models are potentially capable of high-fidelity computations. Thus the major discrepancies between real and simulated scenes are stem from the input data. The first sub-section herein deals with FLIR systems and the second with SAR systems.

Sources of deviation between real and simulated FLIR images

Potential sources of deviations in FLIR images are presented in Table 1.

Table 1: Sources of deviations between real and simulated FLIR images

Sources of deviation	Potential deviations between real and simulated FLIR images
General simulation fidelity	
	All physics based simulation systems are based on a simulated representation of the real world. The simulated sensor image can only be as good as this representation. For example, in some dynamic simulation systems, simulated object-movement may seem unnatural. Such discrepancies between the real world and its model will remain in the sensor-imagery version of the simulation and affect its quality.
"Target" objects	
Structure	Level of detail is usually expressed in terms of the number of polygons or other facets. Simple models may contain a small number of polygons. Additionally, internal parts, including heat-generating parts (e.g., engine), may not be represented.
Materials & texture	Materials and texture can be defined for each polygon. However, the user may not have access to a sufficiently accurate and detailed material and texture model of the object.
Temperature	Temperature can be defined for each polygon. However, the user may not have access to a sufficiently accurate, time-based model of temperatures

	of the object.
Emissivity	Current simulation systems are capable of accurate computation of emissivity as a function of structure, material, texture, and temperature. Thus its resulting accuracy depends primarily on the former variables.
Conduction	This is a common point of weakness in simulation systems. The conduction of heat between object parts is often not represented in the models. The effect may be of particular significance for internal, heat generating parts (e.g., engines).
Reflectance	IR reflectance from most solid materials is small and should not have a significant impact on objects' simulation fidelity.
Time functions	Changes over time can be defined in advanced models. However, realistic data on heat emittance changes over time may not be available.
Background (terrain)	
Terrain	Real terrain can be sampled using topographical data, digital terrain elevation data (DTED) and aerial photography. Simulation fidelity depends on the resolution and accuracy of these sources of information.
Terrain objects	Objects that were included in the aerial photographs of terrain (e.g., roads, buildings, trees, etc.), do not have elevation data and are presented as flat 2D patterns, unless treated as target-objects. Full 3D treatment of terrain objects is rarely available.
Materials & textures	Only few areas are mapped in detail for materials and textures. Typically, the fidelity of background simulation is rather low.
Emissivity	Emissivity can be defined for each polygon. However, accurate emissivity mapping of terrain are rare, limited to specific areas and sometime proprietary (limited distribution). Hence, only a few users may have access to limited sets of emissivity maps.
Thermal transfer	Thermal transfer (conduction) between background objects is usually not represented at all in the model. However, it may not be as important for the terrain as it is for heat generating target objects.
Reflectance	Some natural objects (e.g., water surfaces) reflect IR radiation. Some simulation devices do not simulate this feature.
Time functions	Changes in temperature and emissivity can be fed into the simulation. However, the intricate changes that take place over time in the real environment, cannot be represented.
Atmosphere	
Particles	Atmospheric attenuation of radiation can, in general, be presented. However, the specific effects of various types of particles, in different

	layers of the atmosphere, and their interaction with the type of IR detector, may not be represented. (Atmospheric attenuation models of varying levels of detail exist, e.g., the number of individual bands of the electromagnetic spectrum included in the model. A trade-off is required however, between fidelity of the atmospheric model and computation time).
Platforms and FLIR System	
Platforms	The platform on which the sensor is mounted may impact the line of sight between the platform and the scene (e.g., aircraft vs. tank) and the performance of the sensor system (e.g., motion, vibration, etc.). Simulation systems may not be designed to simulate specific platforms but may be capable of simulating some relevant effects. These effects may have to be fed in manually (e.g., visual angle, jitter, etc.).
Detectors	Different FLIR systems use different detectors for the same range or for different ranges of wavelengths. Simulation models may be able to specify the range of represented wavelengths (e.g., 3-5 microns vs. 8-12 microns), but may not be able to simulate the nuances of differences between the ranges and between types of detectors i.e., spectral sensitivity.
Scanning & signal processing	Various scanning methods (serial, vertical, starring) and various methods of signal processing produce different visual results. Simulation may not reflect the results of specific detectors or signal processing method. Of particular concern is the representation of time delay integration, which results in enhanced signal-to-noise imaging.
Resolution	The final resolution of the image is a product of both spatial resolution of the sensor and the resolution of the display system. Most simulation system may support the definition of different sensor resolutions, but simulation of the display is often ignored.
Interactions	
Objects / background	A major drawback of most physics-based simulation systems is that target-objects and the terrain background are defined separately. This may have several consequences and constitutes a major source of unrealistic FLIR simulation (e.g., lack of object shadows on the terrain, salient contour lines of objects, lack of thermal "smearing" effects due to high thermal contrasts between targets and background).
System / Objects & background	The nature of interaction between targets and background depends also on the nature of the sensor system (e.g., the direction of scanning, the nature of the signal restoration processing). These effects may not be represented at all in simulation systems.

Sources of deviation between real and simulated SAR images

Possible sources of deviations in simulated SAR images are presented in Table 2:

Table 2: Sources of deviations between real and simulated SAR images

Sources of deviation	Potential Deviations Between Real and Simulated SAR Images
General simulation fidelity	
	All physics-based simulation systems are based on a simulated representation of the real world. The simulated sensor image can only be as good as this representation. For example if a low-resolution model of the world is used, the quality of SAR simulation may also be effected. This factor may be of particular importance in the simulation of high-resolution SAR systems (which are more sensitive to details than low-resolution systems).
“Target” objects	
Structure	Level of detail is expressed as a number of polygons and should be related to the resolution of the simulated SAR. Simple models may contain a small number of polygons, which may suffice for simulating low-resolution, but not for high-resolution systems. In particular, the accurate geometry of parts with high RCS should (but may not always) be represented.
Materials & texture	Materials and texture can be defined for each polygon. However, the user may not have access to a sufficiently accurate and detailed material and texture maps of the object.
Radar return	Given a detailed and accurate physical model of the object, including: structure, material and texture and a valid SAR sensor model, the computation of radar return from objects in the scene may be quite accurate for low order reflections. However, high order returns (multi-bounce ray contributions) may not be accurately represented.
Subsurface scattering	Subsurface reflections and their associated interactions may play an important role. For example, the RCS of a treated metal surface is determined by the interactions between the metal and the treated surface (subsurface scattering). Some of these effects may be represented in a generalized manner as a weighted-average between materials (e.g., “paint on metal, “paint on wood” in RadarVision™).
Transmitters	Transmitters (e.g., ground radar) may produce a strong “jammer-like” signal, (depending on the nature of the systems). In some simulation systems, this feature is not be represented.

Background (terrain)	
Terrain	Real terrain can be sampled using topographical data, digital terrain elevation data (DTED) and aerial photography. Simulation fidelity depends on the resolution and accuracy of these sources of information.
Terrain objects	Objects that were included in the aerial photographs of terrain (e.g, roads, buildings, trees, etc.), do not have elevation data and, unless treated as target-objects, are presented as 2D patterns. Full 3D treatment of terrain objects is rare and hard to acquire.
Materials & textures	Typically, simulation models contain or provide access to a database with RCS representation of various natural materials that provide a general "SAR look". Only a few areas in the world are mapped in detail for actual materials and texture. In addition, the representation of human-placed objects (e.g., roads, houses etc.), may be deficient or lacking (e.g., objects represented in 2D instead of 3D).
RADAR System	
	In reality, the variety of radar systems is enormous. The specific parameters of the system determine the nature and the quality of the resulting image. Typical SAR parameters that are represented in simulation systems include: range to center of map (meters); squint angle (degrees); map size (meters); resolution method - including resolution (in meters/pixel) and FFT and PRF for the computation of pixel resolution; motion compensation (perfect to high error); frequency agility (on/off); aircraft speed (knots). The accurate representation of these parameters may have a acute effect on the fidelity of the simulated image (depending both on the completeness and accuracy of the simulation system and on the input of the user).

SECTION VI

FIDELITY REQUIREMENTS AND VALIDATION CRITERIA

In theory, some of the state-of-the-art, physics-based simulation programs, are capable of producing very high-fidelity simulations of sensor imagery. In practice, however, simulation fidelity depends on the completeness and accuracy of all components of the simulation, i.e., the representation of terrain, terrain-objects and human-placed objects, atmospheric conditions, the radiometric equations and the representation of the specific sensor system. As we have shown in Tables 1 and 2, each of these components may affect simulation fidelity.

The efforts required to produce high-fidelity simulations may be tremendous. In particular, detailed and accurate representations of terrain material-maps and "terrain objects" may be very difficult to obtain and may not be available to the user of the simulation system. Therefore, the necessary fidelity of the simulation should be determined by the requirements of the application.

The technical means for creating high-fidelity simulation are necessary but not sufficient. One must also know what to create, i.e., have a criterion for simulation fidelity. As shown below, good criteria may be hard or impossible to obtain.

Fidelity validation criteria

Types of validation criteria

We have defined "fidelity" in terms of the similarity between a simulated image and a reference "real image". There may, however be different types of real world reference images. The following distinctions are proposed:

- ☐ Specific: the reference image (real image) is an image that was acquired under specific conditions (e.g., specific terrain, atmosphere, sensor system, etc.). Simulation must be able to represent many different and highly specific features.
- ☐ Generic: the reference image (real image) is a generic or prototypical image representing a possible or a typical sensor image rather than a specific one. Simulation is required to represent a relatively small set of features.
- ☐ Variable: this is an intermediate category. The reference image (real image) is neither highly specific nor generic. Simulation is required to represent a variety of features but is not required to simulate highly specific conditions.

Availability of validation criteria

We defined the "real world image" as the validation criterion for all types of simulated image. These images may not always be readily available. The user may have access to various recorded or real-time sensor-imagery that may be used as generic or as variable validation criteria. The prospects for specific validation, however are limited and depend either on the availability of good, up-to-date intelligence, or on the existence of large sets of real world images from which specific combinations can be drawn. Furthermore, in many cases simulation must be used because the real image does not yet exist (e.g., in mission rehearsal and sensor system development) and therefore, specific validation may only be performed upon completion of the real task (performing the mission, completing system development, etc.).

Required Fidelity

Required fidelity was analyzed in terms of Bremer's (1992) criteria as defined above. Tractability refers to the ability of the simulation to serve its defined purpose, represent the right data at the right grain size, with the right time stamp and also refers to its usability. Tractability is a relative dimension defined by the purpose of the simulation. It will be defined as high if the simulation contains most of the elements that represent the real situation and *vice versa*. Realism refers to the extent to which the experiences encountered in the simulated environment occur in the real task environment. In the present analysis these two criteria were combined into the term "required fidelity" where tractability denotes the aspects that have to be simulated for any given purpose and realism refers to the required quality of these aspects. (Engagement, the third criterion, deals with motivational aspects and will not be used in the present analysis).

Similarity between objects

Fidelity of simulation is defined by the similarity between a simulated and real object. Similarity is determined in terms of the objects' features: size, shape (contour lines), movement, motion (movement of internal parts), brightness, color (when applicable) and texture. The relations between objects should also be considered: object to background contrast, object location, order, groups of objects, etc.

The magnitude of each of these dimensions and their effects on perceived similarity are ill defined. Shively, Burdick, Brickner and Silbiger (in preparation) have argued that detection is affected primarily by object-to-background contrast, movement and size, while recognition and identification are affected primarily by shape, size, movement and motion, location, color and texture. Similarity may be assessed along similar lines. Salient features that determine detection may contribute to large differences between real and simulated objects, whereas smaller features that determine recognition and identification may contribute to smaller differences.

Levels of fidelity

The level of required fidelity is ranked from low to very high. It expresses the required similarity between various components of the simulated image and the reference real-world image. Following is a general definition of each of the fidelity levels:

- ☐ Very high – the simulated entity looks very similar to the real world entity under all conditions.
- ☐ High – the simulated entity looks very similar to the real world entity under different conditions. It is not required, however, to be specifically adapted to all possible conditions.
- ☐ Medium – the simulated entity look quite similar to possible real world representations of that entity.
- ☐ Low – the main features of the simulated entity (e.g., size, general contrast) look somewhat similar to possible real world representations of that entity.

Types of applications

In this section we propose guidelines and analysis tools that may help a user to determine the necessary level of simulation fidelity. The analysis refers to each of the following applications:

- ☐ Operator training
- ☐ Mission rehearsal
- ☐ System research and development
- ☐ Human factors studies
- ☐ Imagery exploitation

Operator training

Training of sensor imagery users can take place in different environments and for different purposes. We propose to distinguish between general (procedural) training and specific training.

Validation criteria: the simulated image should always be validated against a “real image”. As we will show below, sometimes the required “real image” is a specific image, acquired under specific space, time and sensor-system conditions. Whereas, sometimes the “real image” may be a “possible” sensor image, i.e., a more or less generic representation of a sensor image.

Fidelity criteria: the criterion for required fidelity in all types of training is - expected transfer of experience (training) from the simulation to the performance of real missions

with the real imaging sensor system.

General training

By “general training” or “procedural training” we refer to two typical situations. First, the simulation may be used for introductory or general acquaintance with a family of sensors (e.g., 8 – 12 micron band FLIR systems). Secondly, there may be a training situation in which sensor imagery is incorporated into a more comprehensive simulated environment (e.g., a flight simulator, where sensor imagery is part of a comprehensive flight training setup). Table 3 presents simulated sensor imagery validation criteria applicable to general training.

Table 3: Validation criteria and fidelity requirements for general sensor image training.

Type & availability of Validation criterion		Rational and comments
Generic / variable		During training the image does not have to represent specific conditions but rather the general appearance of the specified sensor image. However, the image must represent the major features of the sensor and should represent various typical conditions and difficulty levels (e.g., images at good and bad visibility).
Easily available		Various types of real world images can be used as criteria.
Simulated components	Required fidelity	Rational and comments
Target objects	Medium	Target acquisition difficulty should be realistic
Background	Medium	General view and target to background contrast should be realistic.
Atmosphere	Low (variable)	Different (realistic) levels of visibility should be represented, but do not have to represent specific effects.
System	Medium	The image should represent the general look of the relevant sensor system (e.g., 8-12 microns FLIR system).
Interactions	Low	Fine nuances may be ignored.

Specific training

“Specific training” refers to training situations that are aimed primarily at acquiring and improving sensor imagery skills (e.g., training of SAR imagery analysts, FLIR

weapon system operators, etc.). Table 4 presents simulated sensor imagery validation criteria applicable to specific training.

Table 4: Validation criteria and fidelity requirements for specific sensor image training

Type & availability of Validation criterion		Rational and comments
Variable		The system should be capable of representing a wide variety of realistic conditions. It may not be necessary to represent every possible real life situations but rather a representative sample.
Available		A variety of real world images is needed.
Simulated components	Required fidelity	Rational and comments
Target objects	Medium – very high	Depending on the purpose of the system. For general procedures medium fidelity is sufficient. For target acquisition training, very high-fidelity is desired.
Background	Medium – high	Depending on type and purpose of training. For navigation & orientation high-fidelity is required. For target acquisition a more general view representing realistic target-to-background contrast may suffice.
Atmosphere	Medium	A range of expected atmospheric conditions and their effect on image quality should be represented. It may not be necessary, however, to simulate highly specific conditions.
System	High	The image must represent the look of the relevant sensor system and the specific features of different systems (whenever relevant).
Interactions	Medium - high	Fine nuances in the image may be important, especially for expert operators.

Mission rehearsal

Mission planning and mission rehearsal: If a mission environment can be simulated, the operator may use it to plan the mission and rehearse mission tasks before actual conduct.

Validation criteria: the simulated image should be validated against a real image expected during the mission.

Fidelity criteria: the criterion for required fidelity is expected transfer of experience from rehearsal with the simulation to the performance of the real mission.

Table 5 presents simulated sensor imagery validation and fidelity criteria applicable to mission rehearsal:

Table 5: Validation criteria and fidelity requirements for mission rehearsal

Type & availability of Validation criterion		Rational and comments
Specific – variable		The system should be able to simulate the expected conditions during the mission. Otherwise, negative transfer may result. If such realism is not feasible, the system should be used for training (i.e., improving general skills) rather than for specific mission rehearsal.
Hardly available		The real world images exist only after mission completion. Prior validation must be based on the prediction of expected conditions.
Simulated components	Required fidelity	Rational
Target objects	High	Targets should look as similar as possible to their expected representation in the real world.
Background	High - medium	Background should look similar to its expected representation in the real world. The actual importance of this factor depends on the type of simulated sensor and on the type and variability of actual terrain. (I.e., do terrain features play an important role in mission performance?).
Atmosphere	High - medium	Expected levels of visibility and potential sources of noise and interference should be represented. If unknown various conditions can be used as a representative sample.
System	High	The image must represent the specific look of the relevant sensor system.
Interactions	High - medium	The interaction between major simulation components and fine nuances may determine the specific image and play a significant role during the real mission.

Note: In some mission rehearsal applications both high and medium fidelity simulation may be appropriate. While high-fidelity simulation may help in preparing for the details of the mission, medium fidelity simulation may support general orientation in the area of interest and establish a spatial frame of reference. It is crucial, however, for the user to be

aware of simulation fidelity limitations; otherwise, negative transfer of experience may occur.

System research and development

During system research and development, various system components or entire (sub)systems may be simulated in order to test concepts and ideas at an early stage. For example: Sensor system design, sensor system analysis, sensor performance analysis and evaluation and automatic target recognition (ATR) development, research and training. In many cases simulation serves engineering purposes and may not depend on the specific nature of the final image. We will focus on applications that bear on human performance and specifically on ATR. (ATR algorithm development may employ large amounts of simulated imagery, including many targets, imaging geometries and backgrounds, in order to "train" the algorithm to robust performance over a wide range of scenario conditions).

Validation criteria: the simulated image should be validated against the real image expected in the real system under the same specified conditions and parameters.

Fidelity criteria: the criterion for required fidelity is expected transfer from simulation results to the design of the real system.

Table 6 presents simulated sensor imagery validation and fidelity criteria applicable to system research and development:

Table 6: Validation criteria and fidelity requirements for system research and development

Type & availability of Validation criterion		Rational
Specific		The simulated system must be able to simulate the expected products of real system under the same working conditions. Low-fidelity simulation may result in erroneous design guidelines for the real system.
Available - hardly available		Criteria may be available for modifications of existing systems or existing components and may not be available for new systems and components.
Simulated components	Required fidelity	Rational
Target objects	High – very high	Depending on the purpose of simulation. E.g., for ATR simulation, very high simulation fidelity of target objects is required. This may include articulation of parts of the object (turret, guns, hatches, etc.) and the presence of

		variations (e.g., externally mounted fuel cans).
Background	High	Depending on the purpose of simulation. E.g., background components may play a very important role in geological surveys.
Atmosphere	High	Depending on the purpose of simulation. E.g., for ATR specific atmospheric conditions may affect performance and should be represented.
System	Very high	Depending on the purpose of simulation, simulation may often be system specific.
Interactions	High	Depending on the purpose of simulation. E.g., for ATR, target / background parameters and atmospheric parameters may interact and create specific and unexpected results.

Human factors and imagery exploitation studies

Conduct of controlled human-performance studies in the field is challenging and sometimes impossible. Simulated laboratory conditions provide very useful substitutes, at least for preliminary studies. Some examples for the use of simulated sensor imagery are:

- ☐ Studying various image enhancement techniques and their effects on imagery analyst performance (e.g., Kuperman, Brickner and Nadler, 1998)
- ☐ Generate and evaluate softcopy imagery interpretation key materials for use by imagery analysts.

Validation criteria: simulated imagery must provide a representative sample of the real situation that is being simulated. The actual criterion depends on the specific purpose of the study.

Fidelity criteria: the criterion for required fidelity is the expected transfer from simulation results to real behavior results (i.e., valid generalization of research results).

Table 7 presents simulated sensor imagery validation and fidelity criteria applicable to human factors and image interpretability studies:

Table 7: Validation criteria and fidelity requirements for human factors and imagery exploitation studies

Type & availability of Validation criterion		Rational
Variable – Specific		The simulated image must provide a representative sample of investigated effects, and yield similar human behavior. Since this may be hard to determine, it is recommended to rely on actual similarity between a simulated and a real image. Level of specificity depends on study purpose.
Available – hardly available		Criteria may be available for research on existing systems and may not be available for research of new systems and components.
Simulated components	Required fidelity	Rational
Target objects	Medium – very high	Depending on the purpose of simulation, e.g., for target acquisition studies it should be very high.
Background	Medium - High	Depending on the purpose of simulation, e.g., for studying background clutter effects, it should be high.
Atmosphere	Low - high	Depending on the purpose of simulation, e.g., for studying visibility effects, it should be high.
System	Low - Very high	Depending on the purpose of simulation, i.e., study of a specific system vs. study of a general phenomenon.
Interactions	Medium - High	Depending on the purpose of simulation, interactions may affect some parameters that are important for the study.

SECTION VII

INITIAL VALIDATION OF CONCEPTS

The concepts and the proposed simulation fidelity evaluation criteria, were examined with the help of some subject matter experts (SME).

Method

Subject Matter Experts

Eight male SME (expert sensor imagery users) underwent a structured interview based on the checklist described below.

Four, Israel Air Force (IAF) reserve SAR imagery interpreters, were paid for their participation. These subjects had an average of 3 years of experience with SAR imagery. One of them also had 1.5 years of experience with FLIR systems.

Two IAF pilots with both operational and research FLIR and SAR experience, participated voluntarily. They had an average of 6 years of experience with FLIR and 3 years of experience with SAR systems.

Two IAF reserve remotely piloted vehicle (RPV) operators were paid for their participation. They had an average of 2.5 years of FLIR experience.

The checklist

A checklist was designed as a qualitative validation tool that allowed the SME to evaluate the fidelity of given simulation products. The checklist is presented in Appendix I.

The checklist contains the following sections:

An introduction describing the objectives of the present research and defining the concepts that are being used in the checklist.

Personal details of the SME including experience with relevant sensors and a short description of related missions.

Checklists for the evaluation of the required simulation fidelity of various components in a simulated FLIR or SAR system.

Procedure

Based on the checklist, a structured interview was conducted individually with each SME. Each interview lasted 2.5 - 3 hours. The SME was briefed on the objectives of the research program and introduced to concepts of physics-based simulation, components of a simulated image, simulation fidelity, validation criteria and levels of required simulation fidelity. Then his personal details were recorded, including military occupation, familiarity and experience with relevant sensor systems, and the nature of missions performed with each sensor.

The SME was then asked to select a task that can be performed with the simulated version of a familiar sensor system. Each subject referred to two different sensor systems (e.g., FLIR and SAR); or to two different missions with the same system (e.g., reconnaissance and imagery interpretation) or to two different objectives for the usage of the same simulation (e.g., training and mission rehearsal). The researcher filled in the checklist and recorded the SME's comments.

The types of systems, tasks and purposes of simulated application that were investigated over all SME, are presented in Table 8:

Table 8: The types of systems, tasks and purpose of simulated application that were investigated. Numbers in cells indicate the number of cases in the specified category.

Mission	Photo interpretation		Reconnaissance		Target recognition & designation	
Simulation application	Training	Mission rehearsal	Training	Mission rehearsal	Training	Mission rehearsal
SAR	4	1	1	-	1	1
FLIR	1	1	2	-	3	1

Results and discussion

In general, the method proved to be quite effective. The SMEs had no difficulty in understanding the concepts and relating to a hypothetical simulated task in their areas of expertise.

The average results for collapsed groups of each individual cell (from Table 8) are presented in Appendix II. Some of the major comments and insights are presented below. It should be noted however, that these averages do not have real statistical meaning, not only because of the small samples but also because each SME had his idiosyncratic definition of the nuances of the simulated task. Nevertheless, the ratings of required fidelity were quite consistent and tend to support our theoretical analysis. The SME comments provide some insights regarding the relative importance of various components of a simulated sensor image.

Some of the major points are summarized below.

SAR imagery

Fidelity recommendations

1. SAR in general (and in particular the operational SAR systems that were used by the SMEs) are relatively low-resolution systems. As a result, most objects cannot be recognized solely by their radar signature and require supporting information. This information may come from various sources, for example: patterns of objects (e.g., SA-2 missile site); spatial relations with large, easy-to-recognize objects (e.g., objects at an airfield); known geographical location (e.g., is an object present or absent at a previously known location?). The required fidelity of various objects in a simulated image reflects these relations. Radar scattering should maintain correct size and magnitude proportions between various types of objects, but (depending on system resolution) it may not be necessary to provide highly accurate structural details.
2. Fidelity requirements of terrain and background objects depend on their expected role. While many objects are of low importance and may be represented as texture (e.g., forest, rocky ground), some key objects are highly important and require high-fidelity simulation. The relative importance of objects is task specific. Often, however, human-made structures (e.g., roads, airfields, power lines, defense positions, trenches, etc.) may be of high importance. Changes to the natural terrain that are not represented in the digital terrain map (DTM) may be important. With regard to desired fidelity, defensive positions and trenches, for example, are most difficult to simulate.
3. Atmospheric conditions have little or no effect on SAR and do not have to be simulated.
4. Any SAR image is highly dependent on the design parameters of the specific system that is being used. Depending on the purpose of the simulation it may be important to provide high-fidelity simulation of sensor-specific effects. In addition, it may be important (particularly for training purposes) to teach operators how to identify image quality defects (e.g. blur). For these purposes, specific sensor and platform effects should be simulated.
5. Interactions between features in the SAR imagery are of marginal importance and do not have to be simulated.

Applications

The SMEs recommended using simulated SAR imagery for basic and advanced training of imagery interpreters and airborne reconnaissance operators. For mission rehearsal, however, they thought that it might be virtually impossible to create sufficiently high-fidelity simulations. Two SMEs recommended using electro-

optical/photographic images (in the visual band) for learning the terrain, combined with independent SAR images of relevant objects for familiarization with objects-of-interest, patterns of objects, key ground features, etc.

FLIR imagery

Fidelity recommendations

1. Target recognition is the major task in all missions that were investigated in the present validation study. Therefore, it is most important to provide high-fidelity simulation of target objects, including structure, materials and texture, temperature and emissivity. It is also important to represent the variety of possible or at least probable thermal signatures of targets, including changes over time and activity-related changes (e.g., engine operating or not). Heat conduction between parts of the same objects, (e.g., from engine to body) is also of some importance because it creates the continuous, natural-looking representation of objects. This feature, however, is beyond the capability of most simulation systems.
2. For training applications, it is quite important to have a reasonably accurate and realistic looking representation of the terrain. However, it may not be necessary to represent every little detail or to represent highly realistic thermal features of each object.
3. High-fidelity simulation may only be important for objects that play a significant role in the specific task at hand. Similar to SAR, some human-made objects and features may be important for orientation and general understanding of the image. Some of these objects may be relatively easy to simulate (e.g., flat objects like roads, or symmetrical structures like buildings and power poles), while others may be very hard to simulate unless they are represented in the DTM (e.g., trenches, defense positions). The effect of objects on their background (e.g., scars caused by armored vehicle tracks) is an important feature that is beyond the capability of most simulation systems.
4. Atmospheric conditions have significant effects on FLIR. For training purposes it may be desired to represent different levels of visibility (a dominant factor in atmospheric transmission). It may not be necessary, however, to represent highly specific effects of various particles.
5. Various types of FLIR sensor may differ considerably from each other. Therefore, it is important to provide a high-fidelity representation of the sensor of interest.
6. Interactions between the target and the background may be highly important for the understanding of the image. However, as indicated in Section III above, high-fidelity representation of such interaction may be impossible.

Applications

All participating FLIR experts thought that high-fidelity simulated FLIR can be very useful for the training of various types of operators at various levels of expertise (e.g., RPV operation, weapon system operation, tactical airborne reconnaissance, surveillance and target acquisition applications).

Effective simulation must be capable of representing both static (e.g., specific thermal signatures) and dynamic (e.g., changes over time) processes. The possible usage of simulated FLIR for mission rehearsal was controversial among the SMEs. Some thought that the prospects of viewing an unknown area prior to a mission were very attractive. However, given the level of complexity and variability of FLIR images, most SMEs doubted whether it might be possible to create sufficiently high-fidelity simulation for specific purposes (i.e., create a simulated image similar to the real image expected during the mission). Concern was expressed that low-fidelity simulation may lead to negative transfer of performance. Hence, if high-fidelity simulation cannot be achieved, it may be better to avoid full simulation and use part simulation for viewing thermal signatures of expected objects, anticipate weather and time effects on the sensor, etc.

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Appendix I – The Checklist

Introduction and Objectives

The checklist is intended for the conduction of structured interviews with subject matter experts (SMEs), who regularly use SAR or FLIR images as a part of their job. It is designed to evaluate the required fidelity of simulated SAR and FLIR sensor images, for various types of users and various purposes. Fidelity is defined in terms of the similarity between a simulated image and a reference “real image”.

First, let us introduce you to concepts related to the analysis of sensor-system simulation.

- ☐ Real and simulated sensor images.
- ☐ Physics based simulation
- ☐ Components of physics based simulation: terrain, objects / targets, atmosphere, sensor system, interactions between components.
- ☐ Simulation fidelity - sources of deviation between real and simulated images: general simulation fidelity, targets and other objects, background (terrain), atmosphere, platform and sensor system, interactions between components.

Definition of concepts

Types of validation criteria

Specific: the reference image (real image) was acquired under specific conditions (e.g., specific terrain, atmosphere, sensor system, etc.).

Generic: the reference image (real image) is a generic or prototypical image representing a possible or a typical sensor image rather than a specific one.

Variable: an intermediate category. Simulation is required to represent a variety of features but not to simulate highly specific conditions.

Levels of fidelity

Very high – the simulated entity looks very similar to the real world entity under all conditions.

High – the simulated entity looks very similar to real world entities under different conditions, but is not required, simulate all possible conditions.

Medium – the simulated entity look similar to possible real world representations of that entity.

Low – the main features of the simulated entity (e.g., size, general contrast) look quite similar to possible real world representations of that entity.

Personal details and level of professional experience

Name: _____

Age: _____

Gender: _____

Military occupation: _____

Types of sensor systems: _____

Time and level of experiences with each system:

System			
Time			
Level			

The simulated sensor system (to be evaluated)

Name of system _____

Type of system _____

The simulated mission

Name of mission: _____

Description of the mission:

Required simulation fidelity (analytical)

Type of required validation criteria: Specific / Variable / Generic /

Availability of Validation criterion: High / Low/ None

Table 9: Rational and comments – FLIR systems

Simulated components	Sub Components	Required fidelity	Rational and comments
Target objects	Structure, Materials & texture, temperature, & emissivity Conduction Reflectance Time & changing conditions		
Background	Terrain Terrain objects Materials & textures, emissivity Thermal transfer Heat generating objects Reflectance Time functions.		
Atmosphere	Particles		
Platform			
System	Detectors Wavelength Scanning & signal processing Resolution:		

	- Thermal - Spatial Gain / Level		
Interactions			

Table 10: Rational and comments – SAR systems

Simulated components	Sub Components	Required fidelity	Rational and comments
Target objects	Structure Materials & texture Subsurface scattering Transmitters		
Background	Terrain Terrain objects Materials & textures		
Atmosphere			
Platform			
Sensor system	Radar system parameters		
Interactions			

Actual fidelity

(To be applied on specific simulated images).

General comments and suggestions

Appendix II – Checklist results

Appendix II presents average results and comments from the investigated sensor systems and tasks of the present validation study. The three tasks (photo interpretation, reconnaissance, target recognition and designation) produced similar result and were, therefore, combined. The two sensor systems (SAR and FLIR) by two types of tasks (training and mission rehearsal) define the four subtasks presented below.

SAR simulation for training

Number of SME: 6

Type of required validation criteria: Variable (a generic criterion is irrelevant because real, rather than simulated images can be used as generic examples. A specific criterion is not necessary and it is sufficient to present well-selected examples of representative conditions).

Availability of Validation criteria: Medium – high (various real examples are usually available, however, some desired combinations may not be available).

Table 11: Average required validity and comments on a simulated SAR, training task.

Simulated components	Sub Components	Required fidelity	Rational and comments
Target objects	Structure	Medium - high	Small details cannot be seen in SAR, therefore, it is important to simulate the size and magnitude of scattering, and to represent special cues (whenever relevant), other small details are not crucial.
	Materials & texture	High	
	Subsurface scattering	low	Small nuances (e.g. subsurface scattering) are not important.
	Transmitters	Irrelevant	Most SAR systems are not sensitive to other radar transmitters.
Background	Terrain	Medium	Terrain should looks more or less realistic, most specific details may not be necessary.
	Terrain objects Materials & textures	Very high - medium	Terrain objects that participate in interpretation performance (e.g., defense posts) otherobjects are only as important as terrain features.
Atmosphere		Very low	Has no significant effect on SAR

Platform &	Aircraft and flight path	Low – medium	The platform as such is not important, relevant effects should be simulated (e.g., deviations from flight path).
Sensor system	Sensor	High	If training is designated towards a specific system the parameters of this system must be simulated.
Interactions		Low	For practical purposes, the effects are marginal.

SAR simulation for mission rehearsal

Number of SME: 2

Type of required validation criteria: Variable – specific (a specific criterion is desired, i.e., the simulated image should be similar to specific, real SAR images, this goal, however, is unrealistic. A variable criterion may be useful to some extent in simulating relevant components and providing examples of typical conditions).

Availability of Validation criteria: Medium – low (real images of specific conditions are scarce, availability of images for a variable criterion may be higher).

Table 12: Average required validity and comments on a simulated SAR, mission rehearsal task

Simulated components	Sub Components	Required fidelity	Rational and comments
Target objects	Structure, Materials & texture	Medium - high	Small details cannot be seen in SAR, however, some targets may have specific cues that should be represented.
	Subsurface scattering	low	Small nuances (e.g. subsurface scattering) are not important.
	Transmitters	Irrelevant	Most SAR systems are not sensitive to other radar transmitters.
Background	Terrain	Medium	Terrain should look realistic, different types of areas must be distinguishable. Highly specific details may not be necessary. Mission-related terrain objects must be well represented, other objects are only as important as terrain features. Hence, the selection of objects for high-fidelity treatment is mission specific.
	Terrain objects Materials & textures	High - medium	
Atmosphere		Very low	Has no significant effect on SAR
Platform & Sensor	Aircraft and flight path	Low	It must be assumed that the operator is familiar with the sensor, expected image

system	Sensor	Very high	quality, typical malfunctions, etc. The specific quality and parameters of the relevant sensor must be represented.
Interactions		Low	Effects are marginal and practically impossible to predict.

FLIR simulation for training

Number of SME: 6

Type of required validation criteria: Variable (it is important to represent a representative variety and a continuum of conditions. It is not necessary, however, to represent every possible combination of conditions).

Availability of Validation criteria: Medium – high (real examples are usually available, however, some desired combinations may not be available)

Table 13: Average required validity and comments on a simulated FLIR, training task

Simulated components	Sub Components	Required fidelity	Rational and comments
Target objects	Structure Materials & texture Temperature & emissivity	High – very high	Thermal signatures depend on structure, materials, temperature and emissivity. Depending on the purpose of simulation accurate representations of the real targets must be provided.
	Conduction	Medium	Heat conduction between parts of objects creates the smooth, natural looking representation of thermal objects in FLIR.
	Time functions & changing conditions	High - very high	Changes over time and changes due to object condition (e.g., engine operating or not) are very important. However, it may not be crucial to represent the exact conduct of every possible process.
Background	Terrain	Medium	Terrain should look realistic, it must be possible to recognize ground features and differentiate between types of terrain. Highly accurate representation may not be necessary.
	Terrain objects Materials & textures,	High – medium	Mission related terrain objects must be well represented, other objects are only as important as terrain features.

	temperature & emissivity		
	Thermal transfer	Medium	Thermal transfer induces the continuous, natural-looking image. It may also provide important cues for detection and recognition (e.g., shading).
	Heat generating objects	Very high – high	Heat generating objects are central to many military tasks and are therefore, highly important.
	Reflectance	Medium – low	Most objects do not reflect IR radiation, reflectance by water (sea, ponds, etc.) should be represented.
	Time functions.	High	Time related changes (e.g., hour of day / night) must be represented realistically but do not have to represent all possible processes.
Atmosphere	Particles	Medium	Atmospheric conditions have important effects on the image. For training purposes, however, it may suffice to represent various visibility levels without distinguishing between different sources of interference.
Platform & Sensor system	Platform	Medium - high	It is important that the image provides an accurate representation of real viewing conditions (i.e., angle, field of view, movement parameters, etc.)
	Detectors, Wavelength, Scanning & signal processing, Resolution, gain & level	High - very high	The image must represent the specific sensor-system of interest including its functions.
Interactions		Medium	Interactions between objects may provide important cues, e.g., tracks on the ground, shading effects, heat transfer between objects, etc.

FLIR simulation for mission rehearsal

Number of SME: 2

Type of required validation criteria: Specific (it is important to represent the area as it will be during the mission, otherwise, the use of simulation may not be recommended for that purpose).

Availability of Validation criteria: Low (validation can only be performed post-hoc, i.e., after the mission).

Table 14: Average required validity and compiled comments on a simulated FLIR, mission rehearsal task

Simulated components	Sub Components	Required fidelity	Rational and comments
Target objects	Structure Materials & texture Temperature & emissivity	High – very high	Thermal signatures depend on structure, materials, temperature and emissivity. Therefore, target objects should be represented as accurately as possible.
	Conduction	Medium	Heat conduction between parts of objects creates the smooth, natural looking representation of thermal objects in FLIR.
	Time functions & changing conditions	High - very	The conditions during the mission should be anticipated, including time effects and other changing effects.
Background	Terrain	Medium	Given that the mission is defined, it may be possible to invest most of the efforts in relevant rather than in all terrain features.
	Terrain objects Materials & textures, temperature & emissivity	High – medium	Given that the mission is defined, it may be possible to invest most of the efforts in important terrain objects rather than in all objects.
	Thermal	Medium	Thermal transfer generates continuous,

	transfer		natural-looking image. It may also contain important cues for detection and recognition (e.g., shading).
	Heat generating objects	Very high	Heat generating objects are highly important in most military tasks. It may be required to distinguish between very similar objects (e.g., real targets and decoys)
	Reflectance	Medium – low	May be important if the mission takes place near open water bodies (sea, lake, etc.).
	Time functions.	High	Time related changes should be anticipated in order to represent a realistic image of terrain and terrain objects during the mission.
Atmosphere	Particles	High - medium	Visibility conditions during the mission should be anticipated. Alternatively, the operator may prepare for a variety of conditions.
Platform &	Platform	High	The image provides an accurate representation of the relevant features of the platform (e.g., angle, field of view, movement parameters, etc.)
Sensor system	Detectors, Wavelength, Scanning & signal processing, Resolution, gain & level	High - very high	The image must represent the specific sensor-system of interest including its functions.
Interactions		Medium	Interactions between targets and terrain may provide important cues, e.g., tracks on the ground, shading effects, etc.

GLOSSARY

3D	Three dimensional
A/G	Air to ground
ATR	Automatic (assisted) target recognition
C	Centigrade
DFAD	Digital feature analysis data
DTED	Digital terrain elevation data
DTM	Digital terrain map
DRLMS	Digital radar landmass simulation
FFT	Fast Fourier transform
FLIR	Forward looking infrared
InDif	Information difference
IR	Infrared
JND	Just noticeable difference
K	Kelvin
LO	Local oscillator
M	meter(s)
MIDAS	Man-machine integration design and analysis system
OTW	Out-the-window
PC	Personal computer
Pixel	Picture element
PDP	Parallel distributed processors
PRF	Pulse repetition frequency
RCS	Radar cross section
RPV	Remotely piloted vehicle
SA	Surface to air
SAM	Surface to air missile
SAR	Synthetic aperture radar
SME	Subject matter expert
TV	Television
VDM	Visual discrimination model